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ESTIMATING THE NUMBER OF LATENT CRACKS IN PRESSURE TUBE JOINTS AT BRUCE UNIT 2

Report No 83-319-K

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ABSTRACT

A model was built to estimate the number of hydride cracks which might have arisen in the rolled joints of Bruce Unit 2 prior to the stress relieving operation. The model estimated that about 100 such cracks might exist. Since this estimate is based on experiments that were thermally cycled and since cycling did not occur in Bruce, prior to stress relieving the actual number is expected to be substantially lower. A sensitivity analysis of the model showed that it is sensitive to the assumptions of stress levels, probability of initiation and distribution of initiation time. A better estimate could be made if more data were available on these parameters under realistic conditions. Therefore, the recommendation is made to collect more information about these factors under realistic conditions.

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To Mr. B.R. Churchill
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ESTIMATING THE NUMBER OF LATENT CRACKS IN PRESSURE TUBE JOINTS OF BRUCE UNIT 2

1. INTRODUCTION

Pickering Units 3 and 4 have experienced pressure tube cracks which allowed PHT coolant to leak into the surrounding gas annulus system. The cause of these cracks was subsequently traced to delayed hydrogen cracking which occurred in the high residual stress region adjacent to end fittings of the pressure tube rolled joints/1/.

When this cause was discovered, Bruce Unit 2, then under construction, was inspected and it was found that it had similar over-rolled joints. A stress relieving operation was performed which reduced the high residual stresses in the rolled joint region. However, two pressure tubes in Bruce Unit 2 have subsequently cracked with the same failure mechanism. It is believed that these failures are due to delayed-hydrogen cracking originating from cracks that appeared subsequent to rolling but before stress relieving.

The Nuclear Systems Department of Design and Development asked the Statistics Unit to develop a model that attempts to estimate the number of latent cracks currently existing in Unit 2 that could potentially lead to failures. These latent cracks are those that escaped detection prior to the stress relieving operation and grew to a certain size by the time the stress relieving operation was performed.

2. SUMMARY OF EVENTS AT BRUCE

The 960 joints in the 480 pressure tubes in Bruce Unit 2 were originally installed with high residual stresses in the over-rolled joints (see Figure 1). When the cause of the failures at Pickering Units 3 and 4 was discovered, an inspection of the tubes at Bruce revealed the same high stresses. At that time,

for these over-rolled joints, the residual stresses in the rolled joint region were estimated to have a mean value of about 650 MPa and a standard deviation of about 125 MPa/3/.

At about 17 000 h post-installation, an eddy current inspection was performed on the tubes. The detection characteristics of the inspection are shown in Figure 2. Note that the eddy current inspection has a high probability of detecting small cracks only if they are long, (ie, a crack must be longer than 9 mm so that a 0.2 mm deep crack will be detected with a 95% certainty). The eddy current inspection did not reveal the presence of any large cracks/3/.

At about 19 000 h post-installation, a stress relieving operation was performed which reduced the stress levels well below those mentioned above. It was estimated by the Nuclear Systems Department that in tubes with the characteristics of crack growth discussed in Section 3, the stress relieving operation would stop all cracks with depths less than 0.20 mm from subsequently growing/2/. It would have no effect upon cracks with depths greater than 0.20 mm.

Hence, an estimate of the number of latent cracks would be the number of tubes having a crack depth greater than 0.20 mm at 19 000 h post-installation.

3. CHARACTERISTICS OF DELAYED-HYDRIDE CRACKING

Zirconium and its alloys may, under certain conditions, absorb and retain hydrogen from the surrounding environment. When the concentration of dissolved hydrogen in the metal exceeds the terminal solid solubility, the excess hydrogen precipitates as platelets of hydrides. If the stress in the material exceeds a threshold level, these hydrides would reorient themselves in the radial direction about a defect on the surface and a crack may be initiated. When the crack has reached a critical size, stable leaking of the tube may occur.

There are, two stages in the cracking process:

- crack initiation, the time until the crack first appears,
- crack growth, all subsequent expansion of the crack.

Crack initiation time depends upon the internal hydrogen concentration, the terminal solid solubility, the stress levels, and the temperature.

Crack velocity, taken as the average propagation speed over time ignoring the stepwise process of growth, depends upon the same factors noted above, and also depends upon the temperature history of the joint.

3.1 Crack Initiation

Cracks are not immediately initiated from defects. Rather an incubation period is required during which time the hydride platelets form. As well, because of local differences in the joints, not all defects initiate a crack.

Chalk River Nuclear Laboratory (CRNL) tests/2/ found that test specimens having defects 0.05 mm to 0.20 mm deep had a probability of about 0.3 of initiating in non-stress relieved overrolled joints.

The distribution of initiation times is not known very well. In an experiment originally designed to measure crack velocities, 60% of cantilever beam test specimens had failed by 20 000 h at 70°C. Note that the 20 000 h includes the crack initiation time plus the time for the crack to grow until the test specimen failed.

This experiment also subjected the test specimens to thermal cycling to induce cracking. The effect of this thermal cycling upon the initiation time is not known; however, in accelerated aging tests of other materials, thermal cycling usually decreases the initiation times. As well, thermal cycling is thought to increase the probability of initiation.

Another problem in interpreting the results of the experiment is that it was conducted at 70°C while the pressure tubes were held between 20°C and 30°C during construction. The increased temperature would give the metal an increased terminal solid solubility, thereby decreasing the rate of hydride formation and prolonging the initiation time. The metal also becomes more ductile at a higher temperature, further lowering the tendency to crack, balanced by increase in the diffusion coefficient.

The net effect of these two opposing forces (thermal cycling and temperature) is not known at this time and cannot be predicted with any measure of confidence. This report will use the initiation time found in the experiment as indicative of the actual initiation times.

Several distributions for the initiation time were assessed. It was found that a simple uniform distribution between 0 and 30 000 h adequately fitted the experimental data.

3.2 Crack Velocity

Crack velocity is fairly independent of the stress level, once a critical stress value is exceeded. This critical stress value depends upon the crack depth. The initial stress levels were sufficiently large so that the critical stress value in many

tubes was exceeded for all sizes of crack nucleating flaws until the stress relieving operation at 19 000 h post-installation. At that time, the stress was reduced so that only cracks with depths greater than 0.20 mm would continue to grow.

Crack velocity, however, is strongly dependent upon temperature/6/ (also see Figure 3). Experiments have been conducted which compare the crack velocity of material which has been hydrided so that it exceeds the terminal solid solubility throughout the temperature range, and "as-received" material. The crack velocity is about 1.7 to 2 times larger in the axial direction than the radial direction/2/.

In the present work, the data on "as received" material as shown in Figure 3 was used to fit a linear regression of the logarithm of crack velocity versus 1000/temperature. It was assumed that the logarithm of actual crack velocity is normally distributed about the mean crack velocity for a particular temperature. The raw data and the regression results are shown in Figure 4 and Figure 5. The predicted crack velocities and the 95% confidence intervals for the crack velocities are shown in Table I for temperatures of 30°C, 25°C and 20°C.

The 95% confidence intervals correspond to a factor of between 6 and 7 above and below the mean. Other authors have reported factors in the ranges of 2-3 above and below the mean/2,6,7/. However, the latter reports looked at crack velocity at higher temperatures (>150°C) and did not attempt to extrapolate below the test temperatures. By examining Figure 3, it can be seen that the scatter of the crack velocities in the as-received specimens is much greater than that for the hydrided materials.

The temperature history of a joint also has a large influence upon the crack velocity/2/. If a hold temperature is approached from below, the crack will have a much lower velocity than that predicted by the velocity-temperature relationship. However, if a temperature drop of about 10°C occurs, the crack velocity quickly goes to the velocity appropriate to that temperature. Since, the joints were held between about 20°C and 30°C prior to stress relieving, the crack velocities for temperatures between 20° and 30°C are appropriate.

4. ESTIMATING THE NUMBER OF LATENT DEFECTS

4.1 The Crack Growth Model

The physical model used for a crack growing is that presented in Reference 2 (see Figure 6). It is assumed that cracks will start growing at a surface between 18 and 24 mm from the start of the taper. The crack will grow in both directions for at least 10 mm (for a total length of 20 mm) when compressive forces will stop growth in the outboard direction. This report

is concerned with cracks less than 8 mm in total length, so this will not be a problem. Since the axial velocity is about twice the radial velocity, the crack will be elliptical in shape with an aspect ratio (length:depth) of about 4:1. The stress relief operation, as mentioned earlier, lowered the stresses in the rolled joint area to such levels that only defects with a depth greater than 0.20 mm would be susceptible to any further growth.

4.2 Estimation

4.2.1 Effect of Stress Levels

Cracks are expected to start from a defect-free surface only if the stress levels are greater than about 600 MPa. The residual stress in the joints was estimated to have a mean of about 650 MPa and a standard deviation of 125 MPa. If a normal distribution is used as a model of the stress distribution, then about 65% of the joints had stress levels high enough to allow a crack to start. This yields 0.65 x 960 = 625 joints where potential defects could start.

4.2.2 Probability of Initiation

The probability of a crack initiating given the right conditions was found to be about 0.3. This yields 0.3 x 625 = 190 joints where cracks will start to grow.

4.2.3 Distribution of Cracks at 17 000 h

The distribution of crack lengths at 17 000 h was calculated to see if any large cracks should have been detected by the eddy current analysis.

Every potential crack has two parameters of interest: the initiation time and the crack velocity. If a uniform distribution for the initiation time and a log-normal distribution for the axial crack velocity (ie, the logarithm of the crack velocity is normally distributed) are assumed, then the joint distribution of these is (assuming that they are independent),

$$f(t,v) = \frac{1}{30\ 000}\ \frac{1}{\sigma}\ \sqrt{\frac{1}{2\pi}}\ \frac{1}{v}\ e^{\frac{1}{-2\sigma^2}(\ell n(v) - \mu)^2}$$

where t = initiation time ($t > 0$),
v = crack velocity, ($v > 0$),
$\frac{1}{30\ 000}$ = uniform distribution for initiation time,
μ = mean ℓn(axial crack velocity),
σ = standard deviation of ℓn(axial crack velocity).

To calculate the probability that a crack will have an axial length greater than ℓ by 17 000 h, the above function is integrated over the probabilities that the crack will initiate at a time t, and that the velocity is greater than $V_o = \ell/(17000-t)$, or,

$$\Pr(L>\ell) = \int_{t=0}^{17000} \int_{v=V_o}^{\infty} f(t,v)\, dv\, dt \cdot$$

This integral cannot be reduced to a closed form, but can be evaluated numerically. Table II shows the estimated probabilities of exceeding certain crack sizes.

Note that there are about thirty cracks with lengths greater than 8.00 mm at 30°C. The eddy current analysis used a 9 mm coil, so some of these large cracks may not be detectable, as mentioned in Section 2.

4.2.4 Distribution of Cracks at 19 000 h

The calculations in the previous section can be repeated for 19 000 h post-installation. The results are shown in Table III. Since stress relieving would stop all cracks less than 0.20 mm in depth from growing further, there are about 109 joints with cracks that would not be affected by stress relieving if the tubes were kept at 30°C and those cracks at 17 000 h were not detected and corrected. This would be the number of latent cracks. The effect of temperature is slight with an estimated 103 latent cracks if the tubes had been kept at 20°C.

4.3 Sensitivity Analysis

A confidence interval around the point estimate presented earlier cannot be constructed due to the paucity of any data to support the assumptions made. For example, initiation time is based on an experiment which used thermal cycling to speed initiation and at a higher temperature which may retard initiation. However, each of the steps in the estimation process can be examined and the effect of changes in the assumptions can be estimated.

4.3.1 Effect of Errors in Stress Levels

It was estimated that 65% of the joints had stress levels high enough to initiate cracks. Any change in this figure would cause a proportional change in the number of latent cracks. For example, if the actual percentage of joints having suffi-

cient stress levels was 50%, then the new estimate of the number of latent cracks would be 109 x 50 ÷ 65 = 83 for tubes kept at 30°C.

4.3.2 Effect of Errors in Probability of Initiation

It was assumed that the probability of a crack initiating was 0.3. Any change in this figure would lead to a proportional change in the number of latent cracks. For example, if the actual probability of crack initiation time was 0.5, then the new estimate of the number of latent cracks would be 109 x 0.5 ÷ 0.3 = 182 for tubes kept at 30°C.

4.3.3 Effect of Errors in Crack Initiation Time

It was assumed that the distribution of initiation times followed a uniform distribution between 0 and 30 000 h. If the uniform distribution is retained, but the upper limit is changed, then it can be shown that the effect upon the estimated number of latent cracks will be inversely proportional. For example, if the upper limit is taken to be 60 000 h, then the new estimate number of latent cracks would be 109 x 30 000 ÷ 60 000 = 55 for tubes kept at 30°C.

The effect of using a different distribution for the initiation time is difficult to predict without redoing the numeric integration. However, if the new distribution had a higher probability of initiation before 17 000 h, then a larger number of cracks would survive stress relieving.

4.3.4 Effect of Errors in Crack Velocity

The effect of changing the mean crack velocity and the standard deviation for crack velocity was investigated by simulation. For example, what would happen if the actual mean crack velocity was half of that used or, if the bounds for 95% tolerance intervals were a factor of 3 rather than the 6 to 7 actually used. Table IV compares the results of these changes with the original results for 30°C. The table shows that the effects are not very large at the 0.20 mm depth cutoff in the stress relief operation.

5 SUMMARY AND RECOMMENDATIONS

A model was built to estimate the number of latent cracks in pressure tube joints in Bruce Unit 2. The estimated number of latent cracks still remaining after the stress relieving operation is 109 at 30°C, 106 at 25°C and 103 at 20°C.

Note that the model indicates that a substantial number of very large cracks (about 60 greater than 4.00 mm in length) would be present at 19 000 h. Since only two tubes have failed due to cracks, this may be an indication that the current model of crack growth is not valid for larger cracks. The model also indicates a possible reason for the failure to detect cracks using the eddy current inspection at 17 000 h. It appears that at that time there would be only a few cracks greater than the coil diameter.

The results from this study should be compared with the results of an inspection of over-rolled joints in Pickering Units 3 and 4/8/. These joints were not stress-relieved. Of 441 rolled joints inspected, 82 were found to have cracks. If the joints at Bruce had not been stress-relieved, then this would correspond to a potential 82/441 x 960 = 178 cracks at Bruce. However, the joints at Bruce have been stress-relieved; the potential number of cracks at Bruce should be considerably lower.

As well, one tube used as a calibration tube while stress relieving was being done at Bruce, was stored for 7 years without stress relieving. When it was inspected, it also was found to be cracked. However, the time of cracking is unknown and this experience cannot be readily compared to the results in the report.

A sensitivity analysis showed that the model is sensitive to the assumptions of stress levels, probability of initiation and distribution of initiation time. It is not sensitive to the crack velocity parameters. Paradoxically, the latter is the only assumption with any measure of confidence.

It should be noted that the incubation time and probability of initiation were estimated from experiments that had undergone thermal cycling. Since this cycling did not occur in Unit 2, the actual number of latent cracks may be substantially less.

Because of the sensitivity of the model to the above parameters, it is recommended that further experimental work be undertaken to estimate these parameters under realistic conditions.

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TABLE I

ESTIMATED CRACK VELOCITIES

Temp	Predicted log (crack velocity)	95% Confidence Intervals for predicted log (crack velocity)		Std Dev* about mean
°C	$\log_{10}$ (m/s)	lower $\log_{10}$ (m/s)	upper $\log_{10}$(m/s)	
30	-9.766	-10.554	-8.978	0.370
25	-9.859	-10.664	-9.055	0.377
20	-9.956	-10.778	-9.133	0.386

* 15 degrees of freedom, $t_{15,\ 0.975} = 2.131$
$t_{15,\ 0.95} = 1.753$

TABLE II

SELECTED PERCENTILES OF CRACK LENGTH AT 17 000 h

Axial Crack Length	Radial Crack Depth	Probability of exceeding depth*			Estimated number of joints exceeding depth**		
mm	mm	30°C	25°C	20°C	30°C	25°C	20°C
0.20	0.05	0.55	0.55	0.54	104	104	103
0.40	0.10	0.53	0.53	0.52	101	101	99
0.60	0.15	0.52	0.51	0.49	99	97	93
0.80	0.20	0.50	0.49	0.47	95	93	89
1.00	0.25	0.49	0.47	0.45	93	89	86
2.00	0.50	0.41	0.39	0.35	78	74	67
4.00	1.00	0.30	0.26	0.22	57	49	42
8.00	2.00	0.16	0.13	0.10	30	25	19

* Temperatures are those at which the tubes remained during construction.
** Number of joints at risk is 190

TABLE III

SELECTED PERCENTILES OF CRACK LENGTH AT 19 000 h

Axial Crack Length	Radial Crack Depth	Probability of exceeding depth*			Estimated number of joints exceeding depth**		
mm	mm	30°C	25°C	20°C	30°C	25°C	20°C
0.20	0.05	0.62	0.61	0.60	118	116	114
0.80	0.20	0.57	0.56	0.54	109	106	103
1.00	0.25	0.56	0.54	0.51	106	103	97
2.00	0.50	0.48	0.45	0.41	91	86	78
4.00	1.00	0.36	0.32	0.27	68	61	52

* Temperatures are those at which the tubes remained during construction

** Number of joints at risk is 190

TABLE IV

COMPARING THE PERCENTILES OF CRACK LENGTH
WHEN THE CRACK VELOCITY PARAMETERS ARE CHANGE

Axial Crack Length	Radial Crack Depth	Probability of exceeding given crack length (estimated latent cracks) at 30°C and 19 000 h*			
mm	mm	Original model	Velocity halved	Factor of 3 confidence interval	Both
0.20	0.05	0.62 (118)	0.60 (114)	0.62 (118)	0.60 (114)
0.80	0.20	0.57 (109)	0.51 (97)	0.60 (114)	0.53 (101)
1.00	0.25	0.56 (106)	0.48 (92)	0.57 (108)	0.51 (97)
2.00	0.50	0.48 (91)	0.36 (68)	0.50 (95)	0.38 (72)
4.00	1.00	0.36 (68)	0.21 (40)	0.38 (72)	0.20 (38)

* Number of joints at risk is 190

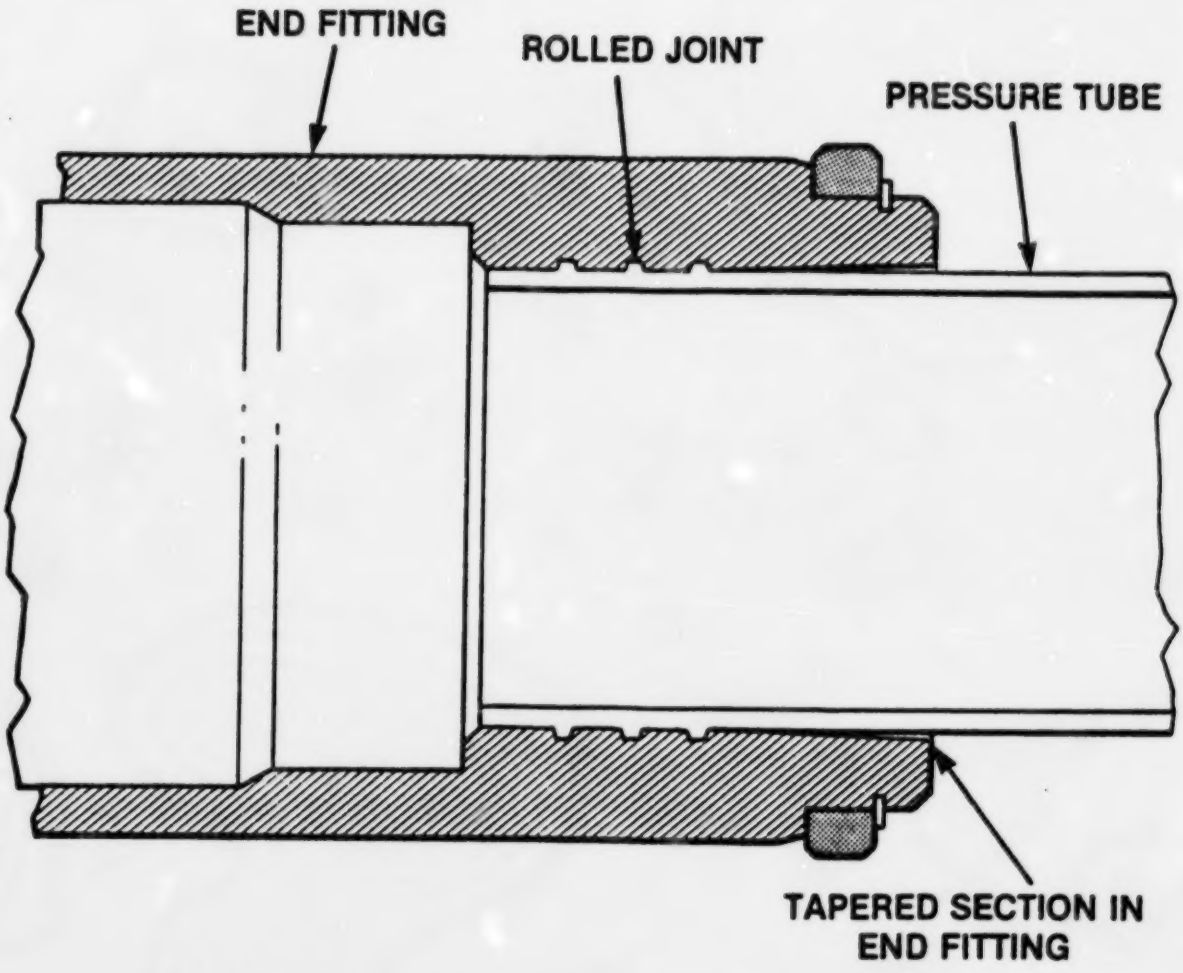

FIGURE 1 BRUCE PRESSURE TUBE ROLLED JOINT

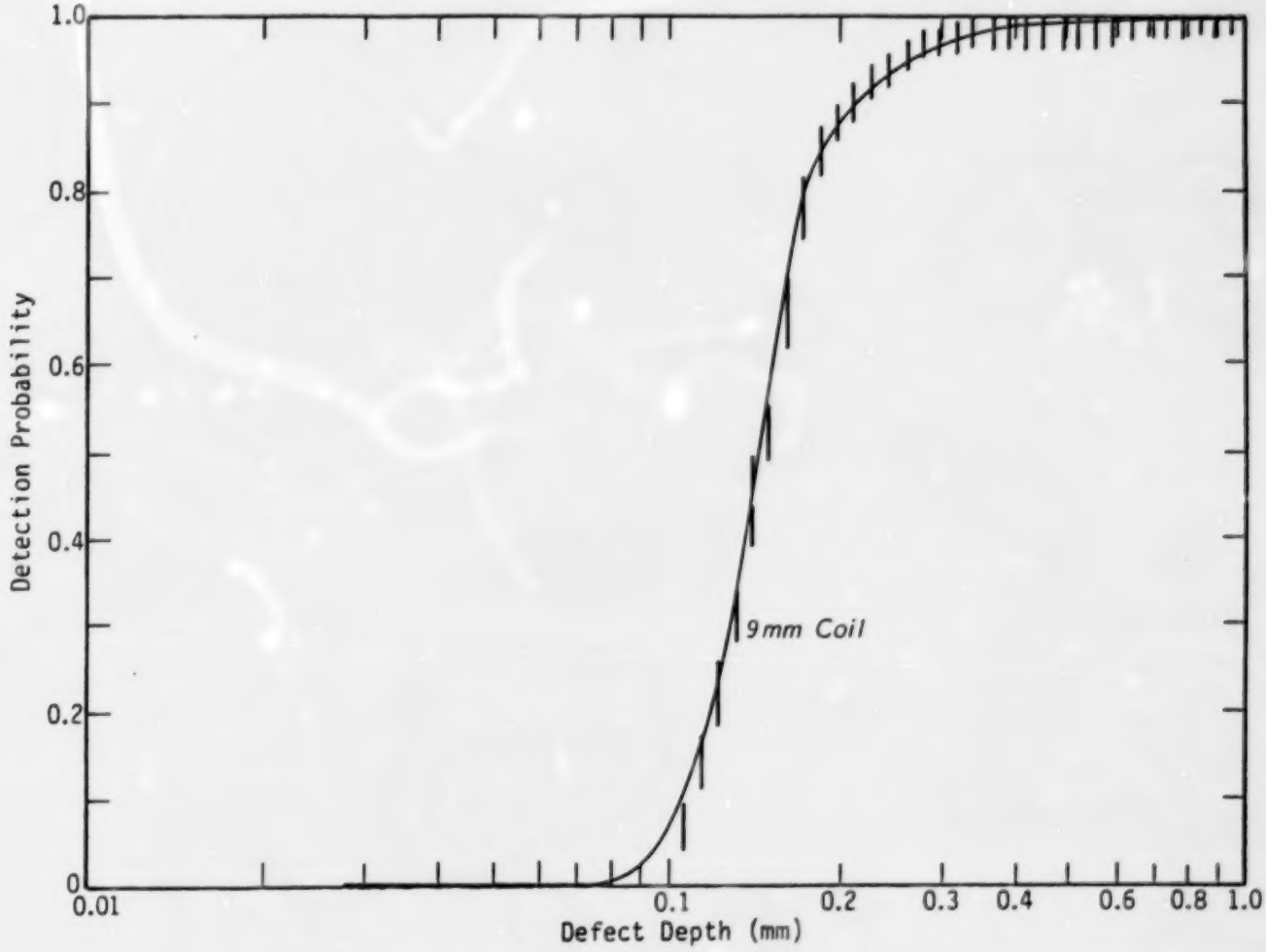

FIGURE 2 QUALITATIVE REPRESENTATION OF DETECTION PROBABILITY FOR REAL MANUFACTURING DEFECTS IN PRESSURE TUBES. THESE CURVES ARE ONLY VALID FOR LONG DEFECTS, i.e., LONGER THAN THE ULTRASONIC BEAM DIAMETER OR EDDY CURRENT TEST COIL DIAMETER.

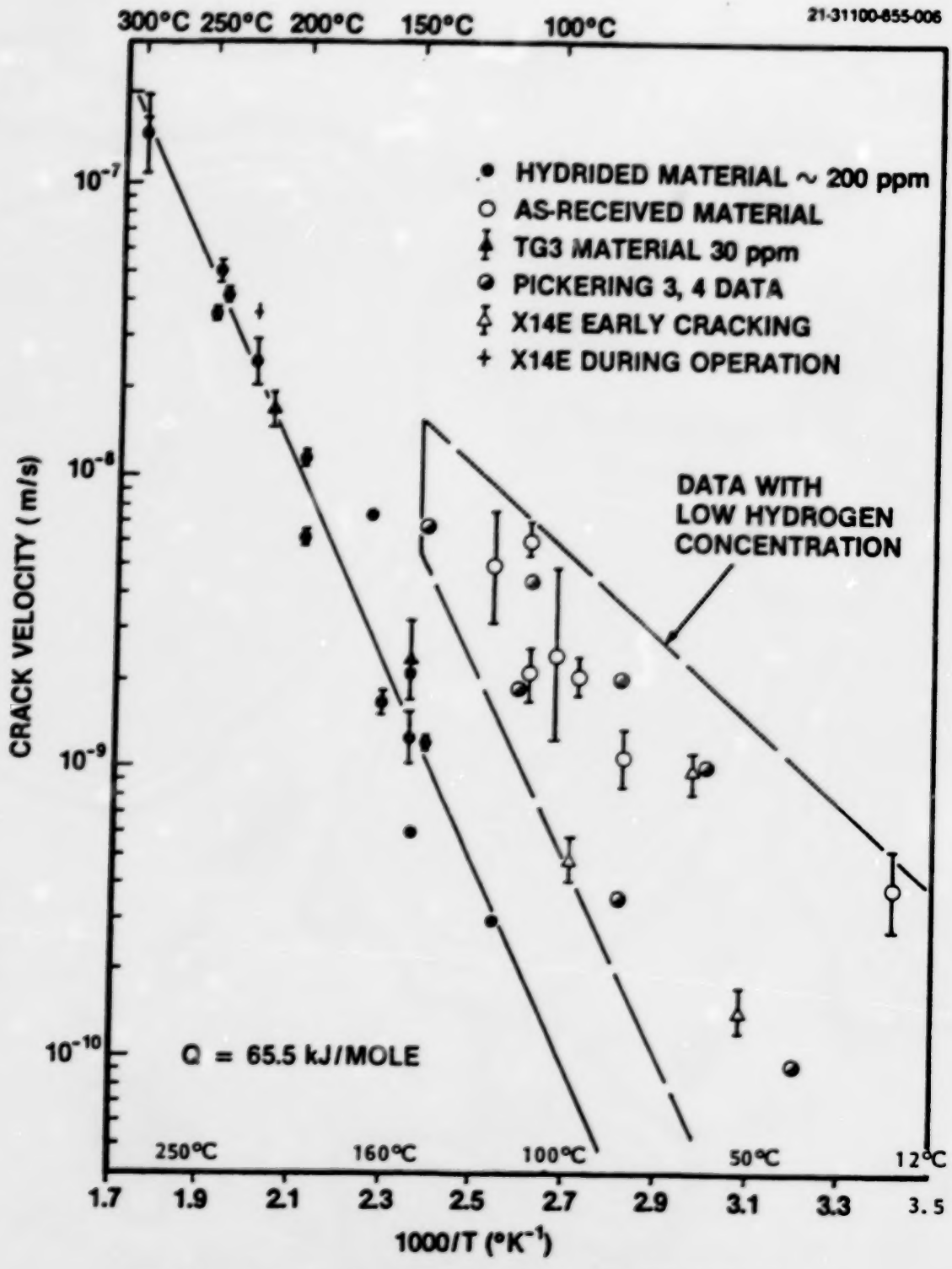

FIGURE 3 TEMPERATURE DEPENDENCE OF DHC CRACK GROWTH RATES IN THE AXIAL DIRECTION

FIGURE 4
RAW DATA USED IN ESTIMATING CRACK VELOCITY

OBS	TEMP C	CRACK VELOCITY M/SEC	LOG VELOCITY	1000/ T(K)	COMMENT	
1	140	6.30000E-09	-8.20	2.42	PICKERING 3-4	==> RAW DATA POINTS
2	120	4.57000E-09	-8.34	2.54	AS RECEIVED	
3	110	1.79000E-09	-8.75	2.61	PICKERING 3-4	
4	110	2.00000E-09	-8.70	2.61	AS RECEIVED	
5	110	3.98000E-09	-8.40	2.61	PICKERING 3-4	
6	110	5.25000E-09	-8.28	2.61	AS RECEIVED	
7	100	2.29000E-09	-8.64	2.68	AS RECEIVED	
8	95	4.57000E-10	-9.34	2.72	X14E EARLY OPERATION	
9	95	1.91000E-09	-8.72	2.72	AS RECEIVED	
10	80	3.47000E-10	-9.46	2.83	PICKERING 3-4	
11	80	1.05000E-09	-8.98	2.83	AS RECEIVED	
12	80	1.91000E-09	-8.72	2.83	PICKERING 3-4	
13	60	9.12000E-10	-9.04	3.00	X14E EARLY OPERATION	
14	60	9.55000E-10	-9.02	3.00	PICKERING 3-4	
15	50	1.38000E-10	-9.86	3.10	X14E EARLY OPERATION	
16	40	9.12000E-11	-10.04	3.19	PICKERING 3-4	
17	20	3.63000E-10	-9.44	3.41	AS RECEIVED	
18	30	.	.	3.30	EST. VEL. 30 C	USED FOR ==> EXTRAPOLATION
19	25	.	.	3.36	EST. VEL. 25 C	
20	20	.	.	3.41	EST. VEL. 20 C	

FIGURE 5
PREDICTED AXIAL CRACK GROWTH RATE AT LOW TEMPERATURES

GENERAL LINEAR MODELS PROCEDURE

DEPENDENT VARIABLE: LOGVEL LOG10(CRACK VELOCITY) (M/S)

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	1	3.07228322	3.07228322	28.82	0.0001	0.657696	3.6534
ERROR	15	1.59899734	0.10659982		STD DEV		LOGVEL MEAN
CORRECTED TOTAL	16	4.67128056			0.32649628		-8.93668835

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE IV SS	F VALUE	PR > F
INTEMP	1	3.07228322	28.82	0.0001	1	3.07228322	28.82	0.0001

PARAMETER	ESTIMATE	T FOR H0: PARAMETER=0	PR > |T|	STD ERROR OF ESTIMATE
INTERCEPT	-4.20807624	-4.76	0.0003	0.88436051
INTEMP	-1.68405378	-5.37	0.0001	0.31369209

OBSERVATION	COMMENT	OBSERVED VALUE	PREDICTED VALUE	RESIDUAL	LOWER 95% CL INDIVIDUAL	UPPER 95% CL INDIVIDUAL
1	PICKERING 3-4	-8.20065945	-8.28568829	0.08502884	-9.04698899	-7.52438759
2	AS RECEIVED	-8.34008380	-8.49320036	0.15311656	-9.23061319	-7.75578752
3	PICKERING 3-4	-8.74714697	-8.60508349	-0.14206348	-9.33316862	-7.87699836
4	AS RECEIVED	-8.69897000	-8.60508349	-0.09388651	-9.33316862	-7.87699836
5	PICKERING 3-4	-8.40011693	-8.60508349	0.20496656	-9.33316862	-7.87699836
6	AS RECEIVED	-8.27984070	-8.60508349	0.32524280	-9.33316862	-7.87699836
7	AS RECEIVED	-8.64016452	-8.72296572	0.08280121	-9.44405846	-8.00187299
8	X14E EARLY OPERATION	-9.34008380	-8.78430933	-0.55577447	-9.50294322	-8.06567545
9	AS RECEIVED	-8.71896663	-8.78430933	0.06534270	-9.50294322	-8.06567545
10	PICKERING 3-4	-9.45967053	-8.97876683	-0.48090370	-9.69504448	-8.26248918
11	AS RECEIVED	-8.97881070	-8.97876683	-0.00004387	-9.69504448	-8.26248918
12	PICKERING 3-4	-8.71896663	-8.97876683	0.25980020	-9.69504448	-8.26248918
13	X14E EARLY OPERATION	-9.04000516	-9.26529479	0.22528963	-9.99316560	-8.53742398
14	PICKERING 3-4	-9.01999663	-9.26529479	0.24529816	-9.99316560	-8.53742398
15	X14E EARLY OPERATION	-9.86012091	-9.42186503	-0.43825589	-10.16340420	-8.68032585
16	PICKERING 3-4	-10.04000516	-9.58843975	-0.45156541	-10.34984178	-8.82703772
17	AS RECEIVED	-9.44009337	-9.95570005	0.51560668	-10.77816964	-9.13323047
18 *	EST. VEL. 30 C	.	-9.76600950	.	-10.55416495	-8.97785405
19 *	EST. VEL. 25 C	.	-9.85926341	.	-10.66359007	-9.05493675
20 *	EST. VEL. 20 C	.	-9.95570005	.	-10.77816964	-9.13323047

* OBSERVATION WAS NOT USED IN THIS ANALYSIS

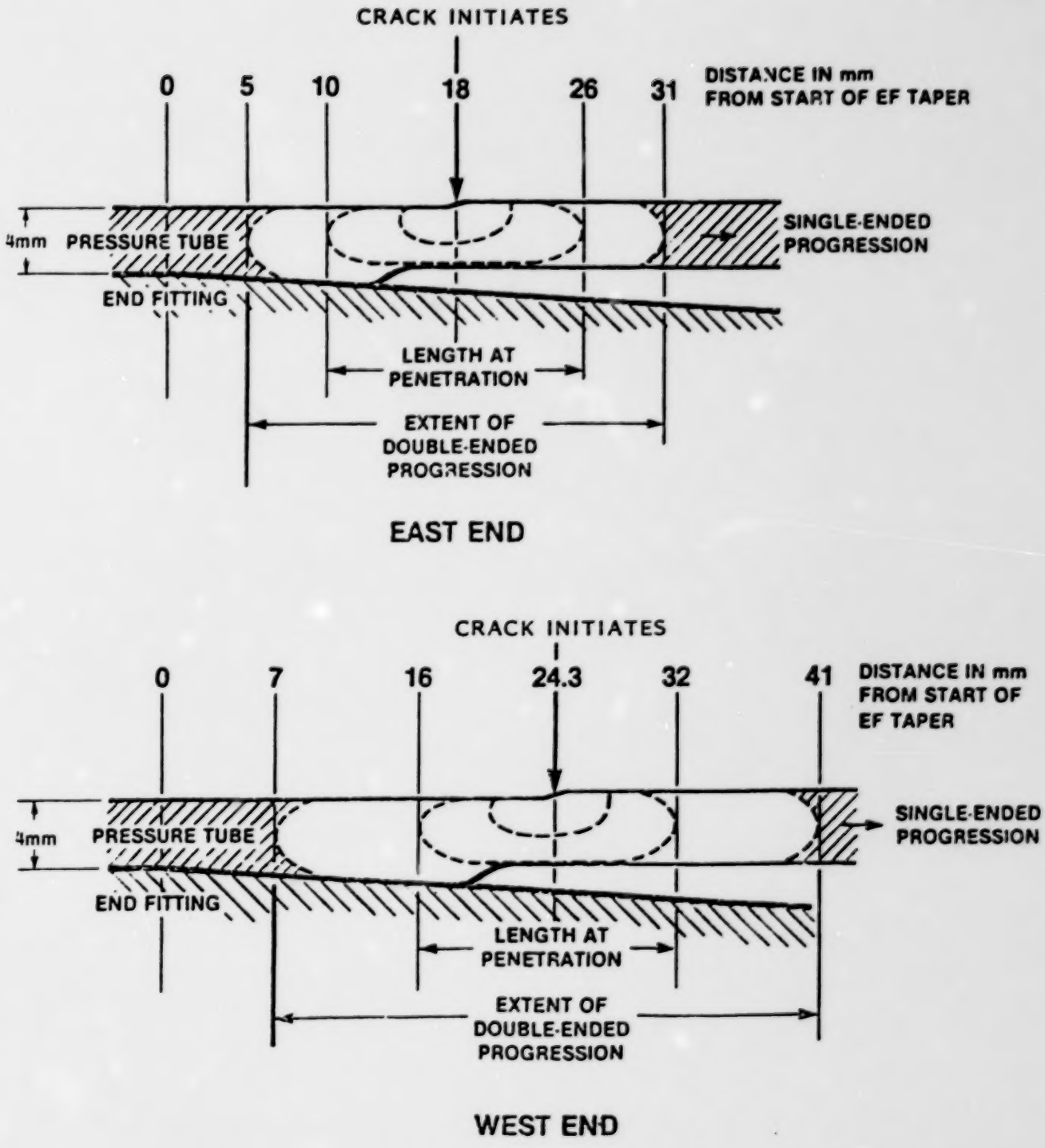

FIGURE 6 SCHEMATIC OF PROBABLE CRACK INITIATION AND PROGRESSION SEQUENCE